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Distractor heterogeneity, attention, and color in visual search

Allen L. Nagy *, Gina Thomas

Department of Psychology, Wright State University, 3640 Col Glenn Highway, Dayton, OH 45435, USA

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Abstract

Experiments were designed to investigate the effects of set size and variation in the chromaticity of distractor stimuli on thresholds for detecting a target stimulus that differed from distractors only in chromaticity. Distractor chromaticities were selected from a line in the isoluminant color plane and targets were selected from lines approximately orthogonal to the distractor line. With uniform distractors thresholds increased with set size as predicted by a signal detection model. When targets and distractors were selected from lines parallel to the Cardinal directions in color space, thresholds were lower with variable distractors than with uniform distractors and variations in the location of the target along the distractor line had no effect on threshold. Results with diagonally oriented distractor lines were similar. Results suggest that many pairs of orthogonal directions in the isoluminant color plane represent independent color coding mechanisms that mediate search. Results also show that information in independent color coding mechanisms tuned to orthogonal directions in the isoluminant plane can be combined to facilitate detection of the target.

Keywords: Color; Search; Attention

1. Introduction

In visual search tasks it is often found that increasing the heterogeneity or variation in the distractor stimuli has a detrimental effect on search performance as measured with accuracy or response time measures (see Palmer, Verghese, & Pavel, 2000). However, some studies suggest that when the heterogeneity of the distractor stimuli is along a perceptual dimension that is irrelevant to the task, it may have little effect on performance (e.g. Pashler, 1988). Treisman (1988) proposed that variation in the distractors would have a negative effect on search performance only if it had some effect on excitation in the feature coding mechanisms used to dif- ferentiate target and distractors. Evidence from threshold studies supports the idea that observers can selectively attend to some feature coding mechanisms while ignoring activity in other mechanisms (see Graham, 1988). A different view was suggested by Duncan and Humphries (1989) who proposed that when target–distractor discriminability was low, increasing heterogeneity in the distractor stimuli would result in decreased search efficiency, but when target–distractor discriminability was high increasing heterogeneity in the distractors would have little effect on performance. Yet another view is suggested by the early literature on color coding in search, which shows that heterogeneity in the color of the distractor stimuli can improve search performance if the variation in distractor stimuli provides useful information to the observer (Cahill & Carter, 1976; Carter, 1982; Carter & Carter, 1981; Christ, 1975; Farmer & Taylor, 1980; Green & Anderson, 1956). Thus heterogeneity in distractor stimuli has been shown to impair performance, have no effect on performance, or improve performance in different studies.

1.1. Attention, selection, and color

It is well known that observers can select some stimuli for attention and ignore other stimuli and studies of attention and selection often show that the unattended stimuli have little or no effect on performance (see Pashler, 1998). It seems clear that location information is effective for guiding attention to relevant stimuli and ignoring irrelevant stimuli. For example Palmer, Aimes, and Lindsay (1993) (see also Palmer, 1994) found that observers could attend to stimuli at cued locations and ignore stimuli presented at uncued locations. Thresholds

* Corresponding author. Tel.: +1-937-773-2626; fax: +1-937-773-3347.
E-mail address: anagy@wright.edu (A.L. Nagy).

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increased with the number of stimuli attended, and the increase was consistent with a signal detection model suggesting that thresholds increased only because of the noisy coding of the stimuli.

The literature on color coding suggests that color may also be used to guide attention to possible target stimuli, and thus facilitate search. Smallman and Boynton (1990) found that adding distractor stimuli to a display had little effect on search performance if the subject knew the color of the target stimulus and the added distractor stimuli differed sufficiently in color from the target, suggesting that color can be effectively used to segregate potential target stimuli from non-target stimuli. Along the same lines, Egeth, Virzi, and Garbart (1984), Friedman-Hill and Wolfe (1995), and Kaptein, Theeuwes, and van der Heijden (1995) found evidence supporting the idea that color may be used to select stimuli for attention and facilitate performance on search tasks.

Pashler (1998) suggests that there have been few studies directly comparing the effectiveness of color with location as a cue for guiding attention, though color cues seem to be as effective as location cues in partial report tasks (Von Wright, 1970). Color may be used to cue locations to which attention is directed (Snyder, 1972; Tsal & Lavie, 1988). However, in studies of conjunction search tasks Treisman and Sato (1990), Wolfe (1994), and Eckstein (1998) discuss evidence in favor of alternative models in which signals in different feature coding mechanisms are linearly summed in a mechanism under attentional control and then used to direct attention to possible targets.

1.2. Neural coding of color and visual search

In the peripheral stages of the visual system, color is coded in three largely independent neural mechanisms (for reviews see (Kaiser & Boynton, 1996; Lennie & D'Zmura, 1988)), that have been referred to as the Cardinal color mechanisms (Krauskopf, Williams, & Heeley, 1982). However, other studies have been interpreted as evidence for higher order color mechanisms tuned to many different directions in color space (e.g. Krauskopf, 1999; Krauskopf, Williams, Mandler, & Brown, 1986; Lennie, Krauskopf, & Sclar, 1990; Webster & Mollon, 1991; Zaidi, 2001; Zaidi & Shapiro, 1993). With regard to performance on visual search tasks, D'Zmura (1991) and Bauer, Jolicoeur, and Cowan (1996a, 1996b, 1999) have suggested that higher order color mechanisms may be necessary to explain performance on visual search tasks with color stimuli.

In a previous study (Nagy, 1999) we asked whether variation in the luminance of distractors had any effect on search for a target that differed from distractors in chromaticity. Results showed that the distractor heterogeneity had little or no effect on response times regardless of the difficulty of the search or the magnitude of the difference between target and distractors. The results were consistent with the idea that varying signals in a Cardinal color mechanism have no effect on search performance if they occur in a Cardinal mechanism other than the one that is used to distinguish the target from the distractors. In the heterogeneous conditions information about luminances of the target and distractors was not used to facilitate the search for a target that differed from distractors in chromaticity.

In a second set of experiments (Nagy & Winterbottom, 2000) we asked whether variation in the chromaticity of distractor stimuli had any effect on searches for targets that differed in luminance. Results for achromatic or white targets were interpreted as support for an independent achromatic mechanism that is insensitive to chromaticity and can mediate search. Results for reddish and bluish targets were interpreted as support for the involvement of higher order color mechanisms, tuned to both chromaticity and luminance. There was no evidence that knowledge of the target chromaticity facilitated search for the luminance defined targets in the heterogeneous distractor conditions. Both studies supported the notion that Cardinal color directions represent independent coding mechanisms in search and suggest that information in different Cardinal mechanisms was not combined in a mechanism under attentional control to facilitate the search.

In the studies described below we use threshold measures rather than response time measures to test further the hypotheses that Cardinal directions represent independent color mechanisms in search tasks and that observers attend only to signals in the Cardinal mechanism that differentiates target and distractors. We chose to extend these studies to threshold measures because it has been shown that well developed signal detection models of threshold can be extended to the search task (see Palmer et al., 2000). Thresholds in each Cardinal color opponent direction were measured at different chromaticities along the other Cardinal color opponent axis as a test of whether the Cardinal axes represented independent mechanisms in search. We also investigated the effect of heterogeneity in distractor color along one Cardinal color opponent axis on thresholds for detecting targets that differed from distractors along the other Cardinal color opponent axis. On the hypothesis that the Cardinal directions represent independent color coding mechanisms, thresholds measured in one Cardinal direction should be independent of the chromaticity along the other Cardinal direction in the uniform conditions. Similarly, on the hypothesis that observers attend only to signals in the Cardinal mechanism that differentiates target and distractors, thresholds in the uniform and heterogeneous conditions should be similar. In the final set of experiments we conducted similar experiments along non-Cardinal axes to determine whether any differences between Cardinal and non-Cardinal directions would be observed.

2. Methods

2.1. Equipment

Stimuli were generated on a 17 inch Nanao T2 color monitor run at a refresh rate of 75 Hz, and a spatial resolution of 832 by 624 pixels. The monitor was driven by a PowerMac 8100 equipped with a Radius Thundercard with 8 bit resolution for each of the phosphor luminances. A Minolta CS-100 Colorimeter was used to measure the chromaticities of the phosphors and to generate look-up tables containing the phosphor luminances as a function of DAC value. The look-up tables were used in conjunction with another computer program which generated the DAC values required to produce a color of desired chromaticity and luminance using a least squared error criterion. This program was used to generate values for the stimuli that were to be used in the experiments and to save them in a text file that could be read by the experimental program.

2.2. Stimuli

The stimuli were small disks 0.12° in diameter presented on a uniform white background (subtending 10 X 13.4° of visual angle) that was continuously present throughout experimental runs. The background field was set to a luminance of 8 cd/m^2 and chromaticity of $x = 0.333$, $y = 0.339$. The disks were presented at locations within an annular region centered on the color monitor. In some conditions only two stimuli were presented on each trial. For these conditions the stimuli were presented to 2.5° to the left and right of the fixation point. The location of the stimulus was randomly jittered from trial to trial so that the x and y coordinates varied by as much as plus or minus 0.38° of visual angle. In other conditions eight stimuli were presented on each trial. The stimuli were separated by approximately 45° of arc around the circle. However the stimulus locations were again jittered as described above. Thus while the mean distance between the centers of the stimuli was approximately 2.1° of visual angle, the minimum distance could be as small as 1.2° of visual angle when eight stimuli were presented.

The luminance of the stimuli was fixed throughout all experiments at 11 cd/m^2. Target and distractor stimuli were set to various different chromaticities. The chromaticities of the stimuli were chosen in the chromaticity diagram described by MacLeod and Boynton (1979). The orthogonal axes of this space are closely related to the two Cardinal color-opponent mechanisms.

2.3. Procedure

In all experiments a yes–no task was used to obtain psychometric functions. Observers viewed the monitor from a distance of 1.4 m in a dark room with flat black walls and flooring so that little was visible other than the stimuli on the monitor. A chin rest was used to stabilize head position. The presentation of small dim fixation cross alerted the observer to the beginning of a trial. The fixation cross was presented in the center of the annular region in which the stimuli appeared. One second after the onset of the fixation cross the stimuli were presented. Color table animation was used to present the stimuli for 15 frames or approximately 200 ms. A half second after the offset of the stimuli a cursor and a vertical line dividing the screen in half appeared. The observer was instructed to use a mouse to place the cursor to the left of the line if the previous trial was judged to contain a target or to the right of the line if the trial was judged not to contain a target. The observer then depressed the mouse button to record the response. After the response the cursor and vertical line were erased and following a short delay the appearance of the fixation cross indicated the beginning of the next trial. A tone was used to give feedback when the observer made an error.

Trials were run in blocks of 50. On half of the trials within each block the target stimulus was presented among the distractors. On the other half of the trials only the distractor stimuli were presented. On trials that contained a target stimulus, the location of the target stimulus was chosen randomly. Typically nine blocks of 50 trials were run in succession to obtain a psychometric function. Generally different target colors were selected for each of the nine blocks of trials in order to span the performance range from 50% to 100% correct. It took approximately 30 min to complete the nine blocks of trials. Observers often collected data for two psychometric functions in one session lasting a little over an hour. Weibull functions were fit to the percent correct for each block of trials plotted against the chromaticity difference between the target and distractor line in order to estimate the chromaticity difference corresponding to 75% correct and this difference was taken as an estimate of threshold.

2.4. Subjects

Results were obtained from four observers with normal color vision in each condition of the first experiment. The author, ALN, a 51 year-old male, and GT, a 40 year-old female graduate student, served as observers in this experiment along with two female undergraduate students (ME and JS) approximately 21 years of age, who were naive to the purpose of the experiments. All had normal color vision and at least a moderate amount of practice at the task before data were collected.

3. Experiment 1: Cardinal color directions

There were two purposes for Experiment 1. First we wanted to determine whether thresholds measured along one Cardinal axis of the cone excitation space were independent of the chromaticity on the other Cardinal axis regardless of set size or the number of stimuli present in the display. Second we wanted to determine whether variation in the distractor chromaticities along one Cardinal axis within a display had any effect on thresholds measured along the other Cardinal axis.

In the first two conditions of this experiment thresholds were measured for stimulus set sizes of 2 and 8. In these two conditions the distractors were all identical and the target differed from the distractor stimuli in its excitation along one Cardinal axis, either *L* excitation or *S* excitation. Thresholds in the *L* direction were measured for violet, greenish-yellow, and white stimuli differing in *S* excitation (open triangles in Fig. 1). Thresholds in the *S* direction were measured for reddish, greenish, and white stimuli differing in *L* excitation (open triangles in Fig. 2). These two conditions are referred to as uniform-2 and uniform-8 below.

In the third condition thresholds at the same five chromaticities used in the first two conditions were measured again with set size of eight. However in this condition the chromaticity of each distractor stimulus on each trial was randomly chosen from one of the Cardinal directions. When thresholds were measured in the *L* direction the chromaticities of the distractors were chosen from a set of 20 chromaticities, separated by approximately equal distances along a line parallel to the *S* axis and extending from the greenish-yellow ($S = 0.298$) to the violet ($S = 2.418$) chromaticities used in the uniform conditions. *L* chromaticity was fixed at approximately 0.664. When thresholds were measured in the *S* direction the chromaticities of the distractors were chosen from a set of 27 chromaticities, separated by approximately equal distances along a line parallel to the *L* axis and extending from the greenish ($L = 0.610$) to the reddish ($L = 0.719$) chromaticities used in the uniform conditions. *S* chromaticity was fixed at approximately 1.0. The number of different colors that could be selected from a line was limited by the 8 bit resolution of the video card. Each of these chromaticities had an equal probability of being assigned to each stimulus in the display with the exception of the stimulus

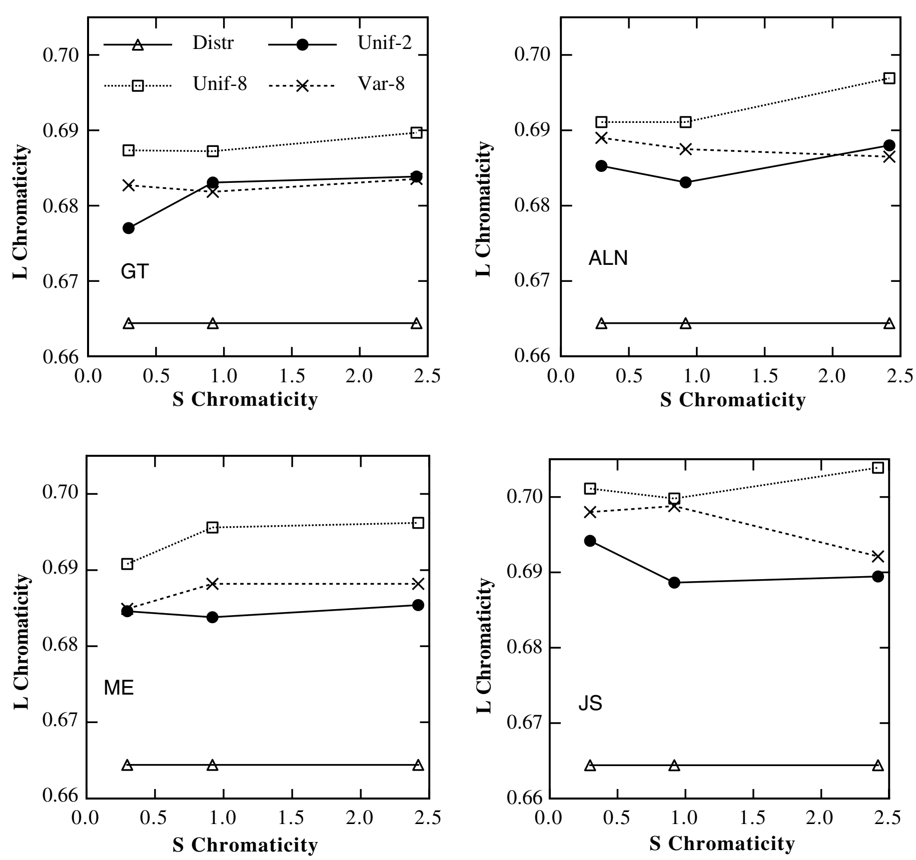

Fig. 1. Thresholds in the $+L$ Cardinal direction for four different observers. Filled circles connected by solid lines indicate the uniform-2 condition; open squares connected by dotted lines indicate the uniform-8 condition; and *x*'s connected by dashed lines indicate the variable-8 condition. Open triangles connected by solid lines indicate the distractor chromaticities.

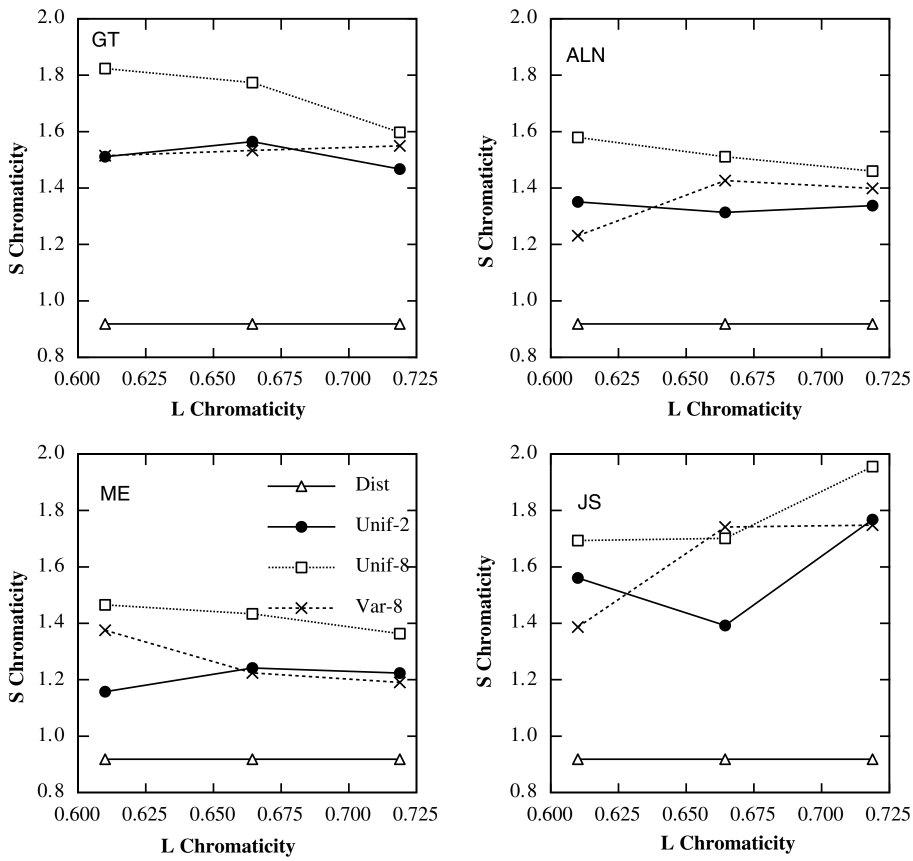

Fig. 2. Thresholds in the $+S$ Cardinal direction for four different observers. Filled circles connected by solid lines indicate the uniform-2 condition; open squares connected by dotted lines indicate the uniform-8 condition; and x's connected by dashed lines indicate the variable-8 condition. Open triangles connected by solid lines indicate the distractor chromaticities.

that might or might not contain the target increment, which was always assigned to one of the stimuli at a randomly chosen location in the display. In half of the trials it contained the target increment while in the other half of the trials it did not. The observer's task was to determine whether a target stimulus of increased L or S excitation occurred on each trial. At the beginning of each block of trials the observer was cued as to the color of the stimulus (i.e. red, green, violet, greenish-yellow, or white) that might or might not contain a chromaticity increment and the color or range of colors of the distractors.

3.1. Results

Thresholds measured in the $+L$ direction are shown in Fig. 1. Results from the 4 observers are shown in separate panels and, in general, are similar for the different observers. The L chromaticity at threshold is plotted along the ordinate against the S chromaticity of the target stimulus along the abscissa. The filled circles connected by solid lines indicate thresholds in the uniform-2 condition. Thresholds in the uniform-8 condition are indicated by open squares connected by dotted lines and thresholds in the variable-8 condition are indicated by the x's connected by dashed lines. Thresholds for the three different S chromaticities of the target were in general similar within each condition. Sequential regression analysis, with display conditions and target colors entered into the regression equation as dummy coded variables, was employed to determine if display condition and target color predicted threshold. Since it was expected that display condition would affect threshold but target color would not, display conditions were entered as a block in Step 1 and target colors were entered as a block in Step 2. Step 1 indicated that the thresholds in the three different display conditions did differ significantly ($R^2 = 0.35$, $F(2,33) = 9.00$, $p = 0.001$). Thresholds in the uniform-8 condition were on average 1.41 times the threshold in the uniform-2 condition ($t = 4.17$, $p < 0.001$). Increasing the set size increased the threshold in the $+L$ direction. Thresholds in the variable-8 condition were on average 0.81 times the thresholds in the uniform-8 condition ($t = 2.78$, $p < 0.01$) and only slightly larger than those in the uniform-2 condition. The introduction of variation in the distractor chromaticities along the S axis reduced thresholds measured in the $+L$ direction. The reduction in threshold was approximately the same magnitude for all three target colors. Step 2 indicated that target chromaticity did not significantly influence threshold (R^2 change $= 0.01$, F change$(2, 31) = 0.279$, $p = 0.76$).

Thresholds measured in the $+S$ direction for the same four observers are shown in Fig. 2. The S chromaticity at threshold is plotted along the ordinate and the L chromaticity of the stimulus is plotted along the abscissa. Step 1 of the sequential regression analysis ($R^2 = 0.22$, $F(2, 33) = 4.52$, $p < 0.05$) indicated that display condition did significantly predict threshold. Thresholds in the uniform-8 condition were on average 1.42 times larger than those in the uniform-2 condition ($t = 2.81$, $p < 0.01$) and the introduction of variation in the L chromaticity of the distractors again reduced threshold. Thresholds in the variable-8 condition were on average 0.76 times the thresholds in the uniform-8 condition ($t = 2.32$, $p < 0.05$) and approximately the same magnitude as those in the uniform-2 condition. In Step 2 (R^2 change $= 0.005$, F change$(2, 31) = 0.10$, $p = 0.90$) the introduction of target color into the regression equation indicated that variation in the target chromaticity along the L Cardinal axis did not predict thresholds measured in the $+S$ direction.

Results in the uniform conditions show that thresholds measured in one Cardinal direction are independent of the stimulus chromaticity along the other Cardinal axis for both set sizes 2 and 8 and are consistent with the hypothesis that the Cardinal axes represent independent mechanisms in search. The increase in threshold with set size is consistent with the predictions of a signal detection model for which it is assumed that: coding of stimuli is independent; signals in different Cardinal mechanisms from each stimulus are independent; signals are noisy with Gaussian distribution; observers attend only to signals in the mechanism that can detect the increment in chromaticity, and the observer uses a maximum decision rule. This model, which has been described in an appendix by Palmer et al. (1993), predicts the growth in threshold as a function of set size with no free parameters. The model predicts that increasing set size from 2 to 8 stimuli should increase threshold by a factor of approximately 1.37. The results in the variable-8 condition, however, suggest that observers must attend to signals in both Cardinal mechanisms in this condition. The introduction of variability in the chromaticity of the distractors reduced threshold, suggesting that observers used information in mechanisms related to both Cardinal directions to detect the target.

4. Experiment 2: Diagonal color directions

The main purpose of Experiment 2 was to determine whether there were any differences between diagonal directions and Cardinal directions. First we wanted to determine whether thresholds measured along one diagonal axis in the cone excitation space were independent of the excitation level along an approximately orthogonal diagonal axis regardless of set size or the number of stimuli present in the display. Second we wanted to determine whether variation in the distractor chromaticities along a diagonal axis within a display had any effect on thresholds measured along an orthogonal axis.

Procedures for the second set of experiments were very similar to those in Experiment 1. Thresholds were again measured in a direction approximately orthogonal to the orientation of the line from which distractor chromaticities were selected, but the distractor lines were oriented at approximately 45° and 135° with respect to the Cardinal axes as illustrated in Figs. 3 and 4. Since chromaticity units in the L and S Cardinal directions are arbitrary and unrelated to sensitivity in the two directions, results from Experiment 1 were used to normalize the units in each Cardinal direction. Mean thresholds for the uniform-8 condition were used to normalize the S and L chromaticity units individually for each observer so that 1 unit on either axis represented the mean threshold from white, which is represented at a normalized chromaticity of $L = 0$, $S = 0$. The distractor lines were then chosen so that they were oriented at approximately 45° and 135° for each individual observer and thresholds were measured in directions orthogonal to the distractor lines. Thresholds were again measured at three different target chromaticities along each distractor line in the same three display conditions (uniform-2, uniform-8, and variable-8) used in Experiment 1. In the uniform conditions with distractors selected from a line oriented at 135° the three distractor chromaticities (open triangles in Fig. 3) appeared to be bluish, white, and yellowish in appearance. Because of the normalization procedure, the chromaticities of the stimuli used for each observer varied somewhat. The chromaticities used for each observer are shown plotted in the MacLeod and Boynton (1979) chromaticity diagram in the lower right hand panel of Fig. 3. In the variable condition the distractor chromaticities were randomly selected, as they were in Experiment 1, from a set of approximately 21 chromaticities along the line connecting the bluish and yellowish chromaticities used in the uniform conditions.

In the uniform conditions with distractors selected from a line oriented at 45°, the three distractor chromaticities along the distractor line (open triangles in Fig. 4) appeared yellow–green, white, and purple. Chromaticities used for each observer are shown in the MacLeod and Boynton (1979) chromaticity diagram in the lower right panel of Fig. 4. In the variable condition the distractor chromaticities were randomly chosen from a set of approximately 20 chromaticities selected from the

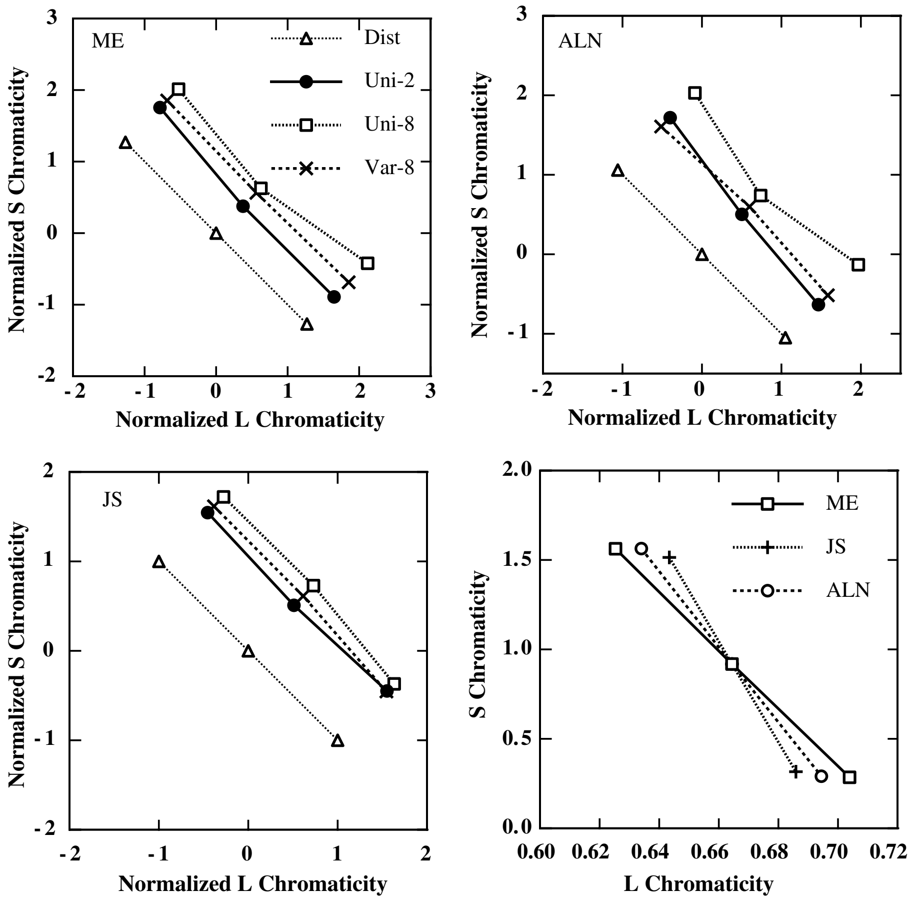

Fig. 3. Thresholds in the 45° direction for three different observers. The lower right panel indicates distractor chromaticities for different observers in the MacLeod–Boynton chromaticity diagram. In the other panels filled circles connected by solid lines indicate the uniform-2 condition; open squares connected by dotted lines indicate the uniform-8 condition; and *x*'s connected by dashed lines indicate the variable-8 condition. Triangles connected by dotted lines indicate the distractors.

line connecting the yellow–green and purple stimuli. Three of the four observers from the first experiment completed Experiment 2.

4.1. Results

Fig. 3 shows the results for distractor lines oriented at 135° and thresholds measured in the 45° direction. Step 1 of the sequential regression analysis ($R^2 = 0.66$, $F(2,24) = 23.4$, $p < 0.001$) indicated that display condition predicted threshold. Increasing set size from 2 to 8 in the uniform conditions again increased thresholds ($t = 6.67$, $p < 0.001$) by a factor of 1.56. The introduction of variation in the distractor chromaticities again reduced thresholds ($t = 4.65$, $p < 0.001$) with the thresholds in the variable-8 condition approximately 0.75 times those in the uniform-8 condition. Step 2 again indicated that target color did not predict threshold (R^2 change $= 0.04$, $F(2,22) = 1.53$, $p = 0.24$).

Fig. 4 shows results for distractor lines oriented at 45° and thresholds measured in the 135° direction. In Step 1 of the sequential regression analysis ($R^2 = 0.20$, $F(2,24) = 3.08$, $p = 0.06$) the prediction of threshold by display condition did not reach significance. However, in Step 2 the prediction of threshold by display condition and target color did reach significance ($R^2 = 0.46$, $F(4,22) = 4.75$, $p < 0.01$). Increasing set size in the uniform condition increased threshold by a mean factor of 1.41 ($t = 2.86$, $p < 0.01$) but introducing variation in the distractor chromaticities for set size 8 did not produce as large a reduction in threshold as in previous experiments. Thresholds in the variable condition were approximately 0.89 times thresholds in the uniform condition ($t = 1.03$, $p = 0.31$). The variable condition resulted in consistently lower thresholds than the uniform-8 condition for observers ME and AN, but sometimes resulted in higher thresholds for observer JS. Thresholds for the yellow–green stimulus ($t = 0.88$, $p = 0.39$) were similar to those for the white stimulus, but thresholds for purple and white targets did differ significantly ($t = 3.159$, $p < 0.01$).

Fig. 5 shows mean threshold distances in normalized units as a function of the direction in which the threshold was measured for the three different display

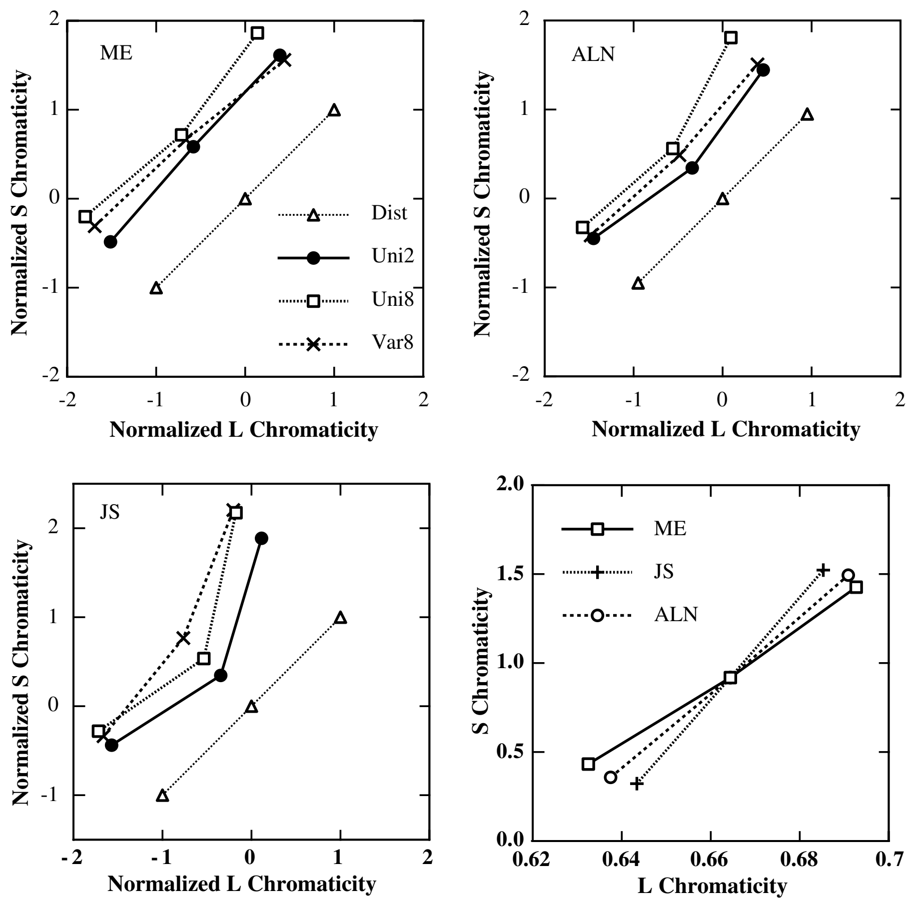

Fig. 4. Thresholds in the 45° direction for three different observers. The lower right panel indicates distractor chromaticities for different observers in the MacLeod–Boynton chromaticity diagram. In the other panels filled circles connected by solid lines indicate the uniform-2 condition; open squares connected by dotted lines indicate the uniform-8 condition; and *x*'s connected by dashed lines indicate the variable-8 condition. Triangles connected by dotted lines indicate the distractors.

conditions. Error bars indicate the standard deviation of the mean. The figure shows that the orientation of the distractor line has little effect on the threshold distance within each display condition. Thresholds with a set size of 8 are clearly larger than thresholds with a set size of 2 (overall mean factor of 1.45) when the distractors are uniform. Thresholds with variable distractors are lower than those with uniform distractors. This reduction in threshold is similar for the 0°, 45°, and 90° directions and slightly smaller for the 135° direction though the magnitude of the threshold in this direction is not significantly different than the thresholds in the other directions for this condition.

5. Discussion

The results of Experiment 1 are in agreement with many previous studies suggesting that the Cardinal directions represent independent color coding mechanisms in simple detection and discrimination tasks. In the uniform conditions, for both set sizes of 2 and 8, variations in the chromaticity of the target stimulus along one Cardinal direction had no effect on thresholds measured in the other Cardinal direction. Thresholds did increase with set size by a factor of 1.42 for thresholds measured in the S direction and by a factor of 1.41 for thresholds in the L direction, consistent with a signal detection model (Palmer et al., 1993), which predicts an increase of 1.37. Results in the uniform conditions of Experiment 1 are consistent with the assumptions and predictions of the signal detection model.

Based on the hypotheses that the Cardinal axes represent independent neural color coding mechanisms and that an observer ignores variations in excitation of feature coding mechanisms that are not used to differentiate the target and distractors (e.g. Treisman, 1988), it would have been expected that heterogeneity in the distractors along one Cardinal direction would have had no effect on thresholds measured in the other Cardinal direction. Alternatively on the Duncan and Humphries (1989) hypothesis, it would have been expected that the heterogeneity in the distractors would increase thresholds because the target–distractor difference was small at

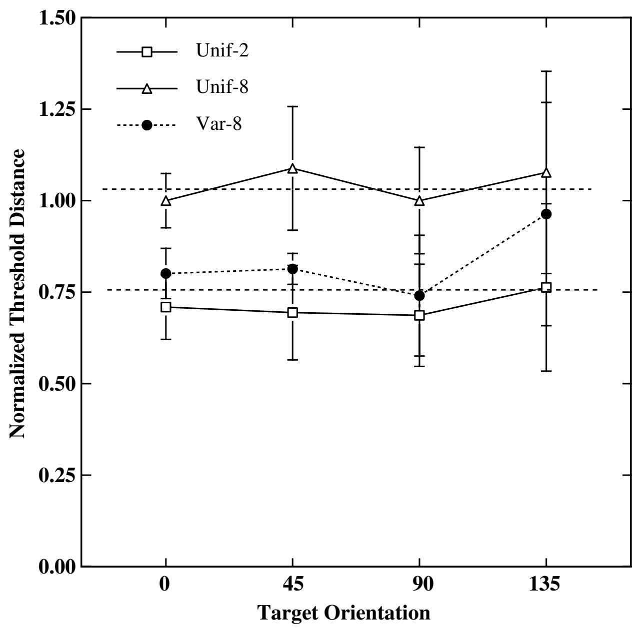

Fig. 5. Mean threshold distances plotted as a function of the direction in which the threshold was measured. Open symbols connected by solid lines indicate the uniform-2 (squares) and uniform-8 conditions (triangle), and the filled circles connected by the dashed line indicate the variable-8 condition. Dashed lines indicate the relationship between set sizes 2 and 8 predicted by the signal detection model described in the text.

threshold. The third alternative, based on the notion that color can be used to select relevant stimuli for attention when the color of the target is known (eg. Green & Anderson, 1956; Smallman & Boynton, 1990), predicted that distractor heterogeneity would reduce thresholds. Results were consistent with the third alternative. Thresholds in the heterogeneous condition were lower than in the uniform condition with set size of 8 and, averaged across all target colors and observers, were just a factor of 1.11 larger than in the uniform condition with only two stimuli. The results indicate that observers monitored signals in both Cardinal mechanisms in order to facilitate detection of the target and lower threshold in the heterogeneous condition. Hypotheses about how the information was combined are discussed below.

The results in these experiments differ from those obtained in earlier experiments with response time measures (Nagy, 1999; Nagy & Winterbottom, 2000). In those experiments distractor heterogeneity along one Cardinal axis either had no effect on searches for targets that differed along another Cardinal axis, or had a negative effect on performance producing longer search times as compared to conditions with uniform distractors. In addition to the difference in performance measures and the fact that the observers could make eye movements in searching for the target in the earlier studies, there were two other procedural differences between these studies and the work described here. In the earlier studies the displays contained many more stimuli (54) and were relatively crowded compared to the displays used in this study. Previous studies have shown that stimulus crowding affects search performance (Monnier & Nagy, 2001; Morgan, Ward, & Castet, 1998; Verghese & Nakayama, 1994). In the earlier studies with heterogeneous distractors several distractor stimuli within each display were similar to the target stimulus along the axis on which the distractors varied. This may have discouraged observers from attempting to use information about the distractors to facilitate performance. Only eight stimuli were presented on each trial in the present study. There were many trials on which there were only a few stimuli similar to the target, because the distractor chromaticities were randomly chosen. Taken together the studies suggest that observers can combine information in different color mechanisms when it is useful. The number of stimuli in the display and the similarity between these stimuli may determine when it is useful. The difference in results from the response time and threshold experiments may have more to do with the differences in display parameters rather than the response measures. Further work will be needed to understand the factors that determine whether distractor heterogeneity improves performance, hinders performance, or has no effect on performance in searches for color targets.

5.1. Selection and attention

Results from Experiment 1 suggest that the varying signals generated by the heterogeneous distractor stimuli could not be used to determine whether a particular stimulus was a target stimulus. They could however be used to determine that a stimulus was not a potential target stimulus because observers always knew which distractor chromaticity might contain the target increment in the other Cardinal direction. A few different models have been proposed for how information in different neural feature coding mechanisms might be combined in mechanisms under attentional control in order to mediate efficient search performance in conjunction search experiments (Eckstein, 1998; Treisman & Sato, 1990; Wolfe, 1994). The models share the property that signals in different feature mechanisms can be selected and summed in mechanisms under attentional control. In one version of this type of model (Wolfe, 1994) attention is then directed sequentially to the stimuli that produce the highest summed excitation working from the highest excitation level down. Another alternative is that the summed excitations are then passed on to a decision process which makes a decision based on the summed signals from all of the stimuli (Eckstein, 1998). Either model could explain the results in the heterogeneous condition of Experiment 1. For example, in searching for a $+S$ target that is at the $+L$ end of the array of distractors observers should sum $+L$ and $+S$ excitation. Attention could then be directed only to the stimuli that produce high summed excitation levels or all of the summed signals could be considered in the decision process. On most trials only a few stimuli should produce high summed excitation levels, and only a few signals will influence the decision process. Consequently, thresholds should be lower than in the uniform condition when the decision must be based on 8 similar signals. For the white stimulus the observer might add an inhibitory signal based on the excitation of the L mechanism to the $+S$ so that the only stimuli that produced large signals were those that produced little excitation in the L mechanism.

The other alternative discussed above (see Egeth et al., 1984; Friedman-Hill & Wolfe, 1995; Kaptein et al., 1995; Smallman & Boynton, 1990) is that signals in one Cardinal color mechanism can be used to select stimuli to be attended. Decisions concerning target presence or absence are then based only on signals generated by the selected stimuli in the other Cardinal mechanism. For example, observers might select only the stimuli that produce large $+L$ signals and then pass $+S$ signals from those stimuli on to the decision process. Since few stimuli would produce large $+L$ signals on most trials, only a few signals would be considered in the decision process.

5.2. Color mechanisms in search

In the second experiment thresholds were measured in diagonal directions with respect to the Cardinal axes and distractor colors varied along lines that were approximately orthogonal to the direction in which the threshold was measured. Results in these experiments were similar to those obtained in the first experiment (see Fig. 5). Thresholds did not vary for the different target colors along a diagonal line in color space in the uniform conditions though there is a hint that the bluish target colors on diagonal lines resulted in somewhat higher thresholds. The mean threshold distance (in the normalized color space) across all conditions and target colors was similar in Experiment 1 (0.82) and Experiment 2 (0.90). In the uniform conditions thresholds increased with set size and the mean increase (factor of 1.48) in Experiment 2 was approximately the same magnitude as in Experiment 1 (factor of 1.42). Thresholds in the heterogeneous condition were lower than in the uniform condition with a set size of 8 and the mean reduction in threshold in Experiment 2 was approximately the same magnitude (factor of 0.82) as in Experiment 1 (factor of 0.78). Observers were able to use the information about the distractors to reduce threshold nearly as efficiently as in Experiment 1.

The fact that varying the distractor color in the uniform conditions had little effect on thresholds measured in the orthogonal direction supports the notion that the mechanisms used to detect the targets are insensitive to the variation in the distractor color and that all pairs of orthogonal directions in the isoluminant plane may represent independent mechanisms. Krauskopf and Gegenfurtner (1992) found similar results in discrimination experiments (see their Fig. 14 and the discussion of it) although their results were not entirely consistent with the notion that there were color mechanisms tuned to many directions in color space. D'Zmura (1991) and Bauer et al. (1996a, 1996b, 1999) have suggested that the mechanisms mediating search for a target that differs from distractors in color are tuned to many different directions in color space based on reaction time measures. The alternative to the higher order color mechanism model is that there are only two different color mechanisms tuned to the Cardinal directions but observers can efficiently combine information from these two mechanisms in mechanisms under attentional control to facilitate search. As discussed above models of this type have been proposed to explain performance on conjunction search tasks and the results of Experiment 1 support the notion that observers can combine information from the L and S Cardinal mechanisms to facilitate search.

Does Experiment 2 clearly support the higher order color mechanism model rather than the attentional model with only two Cardinal color mechanisms? Discrimination thresholds measured in a Cardinal direction typically increase as the chromaticity of the stimuli is moved away from white or the adapting background along the same Cardinal axis (Boynton & Kambe, 1980; Krauskopf & Gegenfurtner, 1992; Miyahara, Smith, & Pokorny, 1993). It has often been suggested that the increase in discrimination threshold with increasing difference between the stimuli and the adapting background is due to increased variance in the responses to the stimuli (e.g. Krauskopf & Gegenfurtner, 1992) or due to a compressive response function in color coding mechanisms (e.g. Shapiro & Zaidi, 1992). Thus we might expect that if signals in Cardinal mechanisms were combined under attentional control, as described in the previous section, in order to detect the targets of Experiment 2, thresholds should be larger in Experiment 2 for chromaticities not near white or the background chromaticity. There is a hint that thresholds are larger for the bluish target colors in Experiment 2 but the increase is neither large nor consistent across observers. Thus the similarity of the results in Experiments 1 and 2 does support the idea that the color mechanisms mediating the detection of the targets are higher level mechanisms than the Cardinal color mechanisms and that they are tuned to many different directions in color space. Treisman (1988) has suggested that the feature modules that mediate visual search are an intermediate stage of visual processing and not the lowest level of feature coding. The experiments reported here, along with other work on color in visual search (see Bauer et al., 1996a, 1996b, 1999; D'Zmura, 1991; Nagy, 1999; Nagy & Winterbottom, 2000), support this hypothesis in suggesting that the color mechanisms mediating search are tuned to many directions in color space. All of these experiments suggest that performance on visual search tasks is mediated at the level of these higher order mechanisms and the Cardinal mechanisms have no special status in visual search, though they might still be regarded as Cardinal in the sense that they represent the coding of color in the early stages of visual processing. The results from both experiments show clearly that information in color coding mechanisms tuned to approximately orthogonal directions in color space can be combined in mechanisms under attentional control to facilitate performance. In further experiments we hope to investigate the different models for combining information in different feature coding mechanisms that were discussed above.

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